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Measurement of the W Mass in e^+e^- Collisions at 183 GeV

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Abstract

The mass of the W boson is obtained from reconstructed invariant mass distributions in W-pair events. The sample of W pairs is selected from 56.812 pb^{-1} collected with the ALEPH detector at a mean centre-of-mass energy of 182.655 GeV. The invariant mass distribution of reweighted Monte Carlo events are fitted to the experimental distributions and the following W masses are obtained:

$$\begin{aligned}
\mathrm{WW} \to \mathrm{q\bar{q}q\bar{q}} \quad & m_{\mathrm{W}} = 80.410 \pm 0.178(\mathrm{stat.}) \pm 0.045(\mathrm{syst.}) \pm 0.056(\mathrm{BE/CR})\ \mathrm{GeV}/c^2, \\
\mathrm{WW} \to e\nu\mathrm{q\bar{q}} \quad & m_{\mathrm{W}} = 80.477 \pm 0.276(\mathrm{stat.}) \pm 0.037(\mathrm{syst.})\ \mathrm{GeV}/c^2, \\
\mathrm{WW} \to \mu\nu\mathrm{q\bar{q}} \quad & m_{\mathrm{W}} = 80.307 \pm 0.300(\mathrm{stat.}) \pm 0.036(\mathrm{syst.})\ \mathrm{GeV}/c^2, \\
\mathrm{WW} \to \tau\nu\mathrm{q\bar{q}} \quad & m_{\mathrm{W}} = 79.926 \pm 0.525(\mathrm{stat.}) \pm 0.085(\mathrm{syst.})\ \mathrm{GeV}/c^2.
\end{aligned}$$

The statistical errors are derived from the single fits to the data in each of these channels. The combination of these four measurements gives:

$$m_{\mathrm{W}} = 80.374 \pm 0.130(\mathrm{stat.}) \pm 0.041(\mathrm{syst.}) \pm 0.028(\mathrm{BE/CR}) \pm 0.022(\mathrm{LEP})\ \mathrm{GeV}/c^2.$$

ALEPH contribution to the 1998 Summer Conferences
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1 Introduction

Pairs of W bosons have been produced at LEP since June 1996, when the centre-of-mass energy of the colliding beams reached the W-pair threshold of 161 GeV. At this energy, first measurements of the W mass at LEP were made using the measured cross sections [1, 2]. A larger sample of W pairs was obtained when running at 172 GeV during October-November 1996, allowing the W mass to be measured from the direct reconstruction of the invariant mass of its decay products for the first time [3].

This paper describes the ALEPH measurement of the W mass by direct reconstruction in both the WW $\to$ q$\bar{\text{q}}$q$\bar{\text{q}}$ (denoted 4q) and WW $\to \ell\nu$q$\bar{\text{q}}$ channels from a much larger sample of data collected in 1997. The integrated luminosities were 0.17 pb^{-1}, 3.92 pb^{-1}, 50.79 pb^{-1}, and 1.93 pb^{-1} at centre-of-mass (CM) energies of 180.83, 181.72, 182.69 and 183.81 GeV respectively. The luminosity weighted CM energy is 182.655 GeV. The letter is organised as follows: firstly, the important properties of the ALEPH detector for this analysis are recalled and a brief description given of the Monte Carlo event generators for the processes involved. Secondly, event selection and mass variable reconstruction for the different channels are described particularly where improvements in earlier procedures [3] have been developed to benefit from the substantially larger statistics. These are the introduction of a 2-dimensional Monte Carlo reweighting procedure for the 4q channel, the full adoption of a new kinematic fitting method to all WW $\to \ell\nu$q$\bar{\text{q}}$ channels, and more complete studies of jet reconstruction systematics. Thirdly, stability checks of the measurement and all studies of systematic errors are described. Finally, the measurements of the W mass in each channel are combined and then added to previously published results at 172 and 161 GeV, taking into account common sources of systematic errors.

2 The ALEPH detector

A detailed description of the ALEPH detector can be found in Ref. [4] and of its performance in Ref. [5]. Charged particles are detected in the central part of the detector. From the beam crossing point outwards, a silicon vertex detector, a cylindrical drift chamber, and a large time projection chamber (TPC), measure up to 31 coordinates along the charged particle trajectories. A 1.5 T axial magnetic field is provided by a superconducting solenoidal coil. A resolution of $\delta p_T/p_T = 6 \cdot 10^{-4} p_T + 0.005$ (p_T in GeV/c) can be achieved. Hereafter, charged particle tracks reconstructed from at least four hits in the TPC and originating from within a cylinder of 2 cm radius and 20 cm length, centred on the nominal interaction point and parallel to the beam axis, are called *good tracks*.

Electrons and photons are identified in the electromagnetic calorimeter (ECAL) by their characteristic longitudinal and transverse shower development. The calorimeter, a lead/wire-plane sampling device with fine readout segmentation and total thickness of 22 radiation lengths at normal incidence, provides a relative energy resolution of $0.180/\sqrt{E} + 0.009$ (E in GeV).

Muons are identified by their penetration pattern in the hadron calorimeter (HCAL), a 1.2 m thick iron yoke instrumented with 23 layers of streamer tubes, together with two surrounding layers of muon chambers. In association with the electromagnetic calorimeter, the hadron calorimeter also provides a measurement of the energy of charged and neutral hadrons with a relative resolution of $0.85/\sqrt{E}$ (E in GeV).

The total visible energy and momentum, and also the missing energy, are evaluated by an energy flow reconstruction algorithm [5] which combines all of the above measurements, supplemented at low polar angles by the energy detected in the luminosity calorimeters. The algorithm also provides a list of charged and neutral reconstructed particles, called *energy flow particles*, from which jets are reconstructed with a typical angular resolution of 30 mrad in space. The jet energy resolution is approximately $\sigma_E = (0.6\sqrt{E}+0.6)\mathrm{GeV}\cdot(1+\cos^2\theta)$, where E (in GeV) and θ are the jet energy and polar angle. The jet energy and angular resolution as well as calibrations were obtained from extensive studies of $Z \to \mathrm{q\bar{q}}$ events both in data and Monte Carlo.

3 Monte Carlo samples

The W mass is extracted by comparing the experimental distributions to the corresponding Monte Carlo distributions, where generated events are processed through a full simulation of the ALEPH detector response and through the same reconstruction chain. The `KORALW`, version 1.21 [6] event generator is used to produce the reference sample of signal events. The complete set of four-fermion (4-f) diagrams is computed with the `GRACE` package [7] with s-dependent running W and Z widths. The `JETSET` [8] package takes care of gluon radiation and hadronisation. Colour reconnection [12, 13] is not included. A sample of 400,000 events were generated with a reference W mass of 80.35 GeV/c^2 at a CM energy of 183 GeV. Four additional samples of 50,000 events each were generated with W masses of 79.85, 80.10, 80.60, 80.85 GeV/c^2 for checking the stability of the results. In addition, large independent samples of signal events were generated with `KORALW` restricted to the doubly resonant CC03 diagrams (cross section = 15.71 pb) for the evaluation of selection efficiencies and jet properties.

Monte Carlo samples at 183 GeV with integrated luminosities corresponding to at least 80 times that of the data, were fully simulated for all background reactions. `PYTHIA` [8] was used to generate 0.50 million $\mathrm{e^+e^-} \to \mathrm{q\bar{q}}(\gamma)$ events with a cross section of 107.6 pb and also 30,000 ZZ and 60,000 Zee events. Events with a flavour content that could originate from WW production are explicitly rejected from the ZZ sample. The $\mathrm{e^+e^-} \to \mathrm{We}\nu$ process was simulated with `PYTHIA`. Two-photon ($\gamma\gamma$) reactions into leptons and hadrons were simulated with the `PHOT02` [9] and `PYTHIA` generators - no events survived the selection cuts for either channel. `KORALZ` [10] and `UNIBAB` [11] were used for dilepton final states.

4 Event selections

In the following sub-sections, the event selections are described for the four types of events considered: $\mathrm{W^+W^-} \to \mathrm{q\bar{q}q\bar{q}}$, $\mathrm{W^+W^-} \to \mathrm{e}\nu\mathrm{q\bar{q}}$, $\mathrm{W^+W^-} \to \mu\nu\mathrm{q\bar{q}}$ and $\mathrm{WW} \to \tau\nu\mathrm{q\bar{q}}$. Purely leptonic events are not considered in this analysis. The expected observable cross sections of signal and background events from these selections together with the corresponding selection efficiencies and purities are summarised in Table 1. The total numbers of events expected and observed of each type are also shown for comparison.

4.1 $W^+W^- \to q\bar{q}q\bar{q}$ events

At 183 GeV the main source of background in the 4q channel is still $e^+e^- \to q\bar{q}(\gamma)$ production, followed by the $e^+e^- \to ZZ$ and $e^+e^- \to WW \to \ell\nu q\bar{q}$ processes. To select hadronic decays, the following preselection cuts are applied: the event longitudinal momentum (p_L) relative to the beam axis must satisfy $| p_L | \leq 0.95(M_{vis} - M_Z)$ where M_{vis} is the reconstructed invariant mass of all observed energy flow particles, and the event sphericity must be greater than 0.03. The remaining events are forced into four jets using the `DURHAM-PE` algorithm [3] where the particles are clustered by their 3-momenta and then the jet 4-momentum recalculated taking the particle masses into account. This procedure combines efficient clustering with minimal bias in the reconstruction of the candidate invariant di-jet masses. Further preselection cuts are applied to these jets, namely the fraction of electromagnetic to total energy in a jet has to be less than 0.95, and y_{34} (the value of y_{cut} where a 4-jet event becomes 3-jet) must be greater than 0.001.

A re-optimized neural network [3] trained at 183 GeV is used to tag the preselected events assigning an output ranging from -1 to +1. There are 19 input variables based on global event properties, heavy quark flavour tagging, jet properties and WW kinematics. None of these variables depends on di-jet invariant masses. It has been found that the discriminating power is improved by applying a 4-constraint (4C) kinematic fit to the events. The signal and $q\bar{q}(\gamma)$ events are well separated by the neural net output. A cut at -0.3 leaves 458 accepted events in the data compared with 441.1 predicted events (362.1 signal and 79.0 background events). One event was also selected as a $WW \to \tau\nu q\bar{q}$ candidate. This event has been kept by both selections to be consistent with the Monte Carlo where vetoing of alternative selections is not applied.

4.2 $W^+W^- \to e\nu q\bar{q}$ and $W^+W^- \to \mu\nu q\bar{q}$ events

The selection follows the procedures used for the 172 GeV analysis [3]. The isolated charged track with the highest momentum component antiparallel to the missing momentum is chosen as the lepton candidate. Loose electron and muon identification criteria and a momentum of at least $21\mathrm{GeV}/c$ are applied to the candidate track. In the case of a candidate $e\nu q\bar{q}$ event, the electron energy is corrected but its direction kept if an associated bremsstrahlung photon is identified. This can occur either as an excess of energy in the ECAL electron cluster or as a separate deposit within 2.5^0 of the electron track impact point on ECAL. In addition, for all events a search is made for isolated final state (FSR) photons associated with the lepton. Such a photon must have an energy above 0.5 GeV, be closer to the candidate lepton than to any other particle or the beam axis and at least 40^0 away from any other good charged track. Their 4-momenta are then combined. Any remaining energy deposits in ECAL within 1.5^0 of the extrapolated lepton candidate track or in HCAL within 2^0 are removed.

The `DURHAM-PE` clustering algorithm is applied to all energy flow particles that are not used to construct the lepton 4-momentum, and these are forced into two jets. After this preselection, the probability for an event to come from the signal process is determined using the momentum of the lepton, the total missing transverse momentum and the lepton isolation from the closest hadronic jet [1]. Events are selected if they have a probability larger than 0.4 to be either a $e\nu q\bar{q}$ or a $\mu\nu q\bar{q}$ event. These cut values are determined using Monte Carlo, such that the expected error on the W mass is minimised. After these selections, 132 and 105 events remain in the electron and muon channels respectively. Monte Carlo studies correspondingly predict 122.3 (109.5 signal, 12.8 background) and 118.8 (112.6 signal, 6.2 background) events in good agreement.

4.3 WW $\to \tau\nu q\bar{q}$ events

The event selection procedure is based closely on methods developed earlier for the extraction of the cross section in this channel at 161 and 172 GeV. In summary, an event is selected if it passes a series of preselection cuts [1] and if it satisfies either a topological or a global selection [16]. Unlike the cross section analysis, a τ jet is always searched for as it is required for the measurement of the W mass. The event is also vetoed if it is selected by either the e or μ selections, so that the sample is independent. The number of events selected is 87 within 1.5σ of the Monte Carlo prediction of 101.9 (91.4 signal and 10.5 background).

Table 1: Expected observable cross sections for various processes after selection cuts. The event numbers shown correspond to an integrated luminosity of 56.812 pb^{-1}. The quoted efficiencies are determined using CC03 events for all channels with $m_W = 80.35$ GeV/c^2. For the 4q channel, all events containing W decays are treated as signal. In the e and μ channels, only events of the appropriate type are considered as signal; whereas for the τ channel, e and μ events which pass the cuts and fail their own respective selections are included as signal.

	σ_{cuts} (pb)			
Process	4q sel.	e sel.	μ sel.	τ sel.
WW $\to q\bar{q}q\bar{q}$	6.310	0.001	0.001	0.011
WW $\to e\nu q\bar{q}$	0.008	1.927	0.001	0.165
WW $\to \mu\nu q\bar{q}$	0.021	0.003	1.981	0.138
WW $\to \tau\nu q\bar{q}$	0.036	0.072	0.073	1.294
WW $\to \ell\nu\ell\nu$	0.000	0.003	0.002	0.000
$q\bar{q}(\gamma)$	1.203	0.057	0.012	0.091
ZZ	0.188	0.011	0.014	0.034
Weν	0.000	0.009	0.001	0.054
Zee	0.006	0.060	0.002	0.006
$\tau\tau$	0.000	0.010	0.004	0.000
2-photon	0.000	0.000	0.000	0.000
Predicted events	441.1	122.3	118.8	101.9
Observed events	458	132	105	87
Efficiency (%)	88.9	82.3	84.9	69.4
Purity (%)	82.1	89.5	94.8	89.7

5 Invariant mass reconstruction

A high statistics study of reconstructed jet energies in two-jet events at the Z shows that 46 GeV jets are well simulated at all polar angles with the largest discrepancy (1.5%) being in the overlap region between barrel and endcaps. Before kinematic fitting is applied, this fractional discrepancy is parametrised as a function of θ and used to match more precisely the Monte Carlo reconstructed jets to the data.

5.1 $\mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}q\bar{q}}$ events

5.1.1 Kinematic fitting

Following a procedure developed previously [3], a 4C kinematic fit is performed to correct the reconstructed jet momenta and thus improve the dijet mass resolution. The total visible energy flow is fixed to the CM energy given by LEP and the energies of jets are assumed to scale in the ratio of their fitted to reconstructed momenta. Average correction coefficients derived from Monte Carlo are applied to the measured jet momenta and directions to account mainly for loss of particles in the regions of the detector close to the beam axis. These coefficients are the three fit parameters for each jet and are defined such that their spread from the average values determined for each bin of jet energy and polar angle, θ, are Gaussian with minimal correlation. For all data events the kinematic fit converges satisfactorily producing a flat χ^2 probability distribution above 5% which is well described by the Monte Carlo.

5.1.2 Jet pairing

For each selected event, the four jets are coupled into two di-jets in three different ways. For each of these combinations, two rescaled 4C masses are determined. The rescaled mass is given by: $m_{ij}^{\mathrm{resc}}/m_{ij} = E_b/(E_i + E_j)$, where E_b is the beam energy and E_i, E_j are the jet energies. The jet pairing algorithm selects the combination with the smallest difference between the two rescaled masses unless this combination has the smallest sum of the two di-jet opening angles. In this case, the combination with the second smallest mass difference is selected. Both masses for the selected combination must lie within the mass window 60-86 GeV/c^2 and at least one of the two masses must be between 74 and 86 GeV/c^2. If this condition fails then the second combination is accepted instead provided its two masses satisfy the window criteria; otherwise the event is rejected. The efficiency of this algorithm to find the correct combination in selected signal Monte Carlo events is found to be 86.9%. At this level, the benefit of adding a second combination which satisfies all cuts is marginal. The order of the two masses in the selected combination is then randomised. The final number of events accepted by the pairing algorithm is 383 compared with the CC03 reference Monte Carlo prediction of 367.5 (312.9 signal and 54.6 background events). Table 2 shows the predicted fraction of signal events passing all analysis cuts and the final purities achieved in the event sample used for the mass extraction.

5.2 $\mathrm{WW} \rightarrow \ell\nu\mathrm{q\bar{q}}$ events

A new kinematic fitting package has been developed to perform a 2-C fit where the di-jet and lepton-neutrino invariant masses are forced to be equal. The effects of ISR are neglected. The contribution to the χ^2 from each jet is built using 4 distance variables:

$$\triangle\beta, \triangle E, p_T^{(\theta)}, p_T^{(\phi)}$$

which describe the deviations due to detector resolution of the measured from the *fitted* jet velocity and energy respectively, as well as the transverse momentum of the measured jet relative to the *fitted* jet both in θ and ϕ. These variables are used to describe the τ jet with $\triangle\beta$ set to zero and also the electron or muon in those events where calorimetric energy is added to the track. Otherwise, the latter cases are described by the variables:

$$\triangle 1/r, \triangle tan\lambda, \triangle\phi^0$$

which are the deviations of the measured from the fitted lepton inverse radius of curvature, dip angle and azimuthal direction at the event vertex. Using the 2 constraints, the number of free parameters in the fit is reduced to 9 chosen such that their physical ranges are minimally correlated. The phase space employed in the search for a minimum χ^2 is then well defined. The full covariance matrix is used to describe the residual correlations between these parameters.

Using an independent sample of CC03 generated WW events, the offsets and resolutions in all these variables are parametrised separately for each channel and particle type as a function of energy and polar angle. The resolutions are adequately described by Gaussians. If the fit converges successfully, then a second minimisation is performed using transformed physical parameters which include the W mass so that its fitted error can be obtained for each event. In the case of the e and μ channels, events with a χ^2 probability less than 2% are excluded. This improves the sample purity and significantly reduces the systematic error from calorimeter miscalibrations. For all channels, the fitted mass must lie in the window 74 - 91.5 GeV/c^2.

For the e and μ channels respectively, 28 and 23 events fail the χ^2 probability cut and a further 8 and 7 events lie outside the mass window. For the τ channel, 16 events fail to converge successfully and a further 14 events lie outside the mass window. The final numbers of events remaining from each channel for the W mass measurement and the corresponding predictions from the Monte Carlo after the final mass window cut are given in Table 2. They are consistent with the data and show that the events passing all cuts contain a smaller proportion of background than the initially selected samples.

Table 2: Final numbers of events (signal + background) chosen after all analysis cuts for the determination of the W mass in each channel. The corresponding CC03 Monte Carlo predictions (normalised to an integrated luminosity of 56.812 pb^{-1}) are tabulated together with the expected purities and fraction of signal events passing all cuts in each channel.

Process	4q	e	μ	τ
Predicted events	367.5	88.5	91.1	73.0
Observed events	383	96	75	57
Accepted (%)	76.9	64.6	67.9	51.0
Purity (%)	85.1	97.1	98.8	91.9

6 Extraction of the W mass

The W boson mass is determined from the hadronic and semileptonic channels separately and then combined taking into account correlations in the systematic errors. For each channel, a binned Monte Carlo reweighting procedure developed earlier [3] is employed to find the value of m_{W} which best fits the observed invariant mass distribution. Selected Monte Carlo signal events from the large 4-f reference sample are reweighted using CC03 matrix elements according to the single parameter to be fitted, m_{W}. The W width is set to 2.09 GeV/c^2 at 80.35 GeV/c^2 and varies with m_{W} as described in Section 3. Background Monte Carlo samples are included in the fit.

The statistical error in m_{W} is computed from the single fits to the data distributions. Also, a large number of Monte Carlo subsamples are studied, each with the same number of events as the data, to evaluate the expected error from the RMS spread of fitted masses and the distribution of fit errors obtained.

6.1 The $\mathrm{q\bar{q}q\bar{q}}$ channel

In the analysis of the 172 GeV data [3], the reweighting procedure was applied to two rescaled mass distributions independently (denoted the '1-D' method). These were each filled by one mass per event selected randomly. The final mass was the weighted average taking into account the correlation between the two fitted masses using the Monte Carlo subsamples.

The higher statistics at 183 GeV allow a true 2-dimensional reweighting to be performed with the two rescaled masses per event (denoted the '2-D' method). The event-by-event correlations in the data are then properly accounted for and lead to an improvement in statistical precision compared with the '1-D' method of approximately 10%. The log-likelihood fit is now performed using a binned 2-dimensional probability density function within the mass region 60-86 GeV/c^2 as defined by the pairing algorithm (see section 5.1). The bin sizes for the Monte Carlo events are chosen dynamically and separately for signal and summed backgrounds so that the number of events per bin for each case is approximately constant. A stable mass value and statistical error are obtained when the minimum number of Monte Carlo signal events in any bin is 60. To evaluate the expected error, 200 independent Monte Carlo subsamples are fitted individually to the same reference sample.

The small residual background (0.5%) of semileptonic events is also reweighted.

6.2 The $\ell\nu\mathrm{q\bar{q}}$ channels

For each channel, the same procedure is employed as in ref. [3], namely binned 1-D Monte Carlo reweighting to the distribution of the 2C fitted masses within the region 74 - 91.5 GeV/c^2. For the e and μ channels, fixed bins of 0.5 GeV/c^2 are used whereas for the τ channel varying bin intervals in the range 0.2 to 1.0 GeV/c^2 are applied depending on the density of Monte Carlo events.

7 Consistency and stability checks

7.1 Reproducibility of the reweighting procedure

The accuracy of the reweighting procedure is tested by comparing the fitted mass obtained from each of the 5 independent Monte Carlo samples generated with input masses between 79.85 and 80.85 GeV/c^2. The relationship between the fitted and true masses is found to be linear for all channels over this range. Straight line fits give slopes of unity within a precision of 2% for the 4q channel and 4% for the $\ell\nu q\bar{q}$ channels with no significant offsets observed. For the 4q channel, the slope of the straight line and hence the values of the fitted mass and error depend on the binning of the given sample of reference Monte Carlo events. Biases were eliminated by ensuring a minimum number of events per bin (see section 6.1). For simplicity, CC03 matrix elements are used in the reweighting procedure instead of 4-f matrix elements. Replacing them with 4-f matrix elements generated by `EXCALIBUR` [14] in the e, μ and τ channels produced small shifts in the fitted masses of 10, 0 and 9 MeV/c^2 respectively. The absence of any significant non-linearity shows that CC03 matrix elements are sufficient for all channels at present.

7.2 Event selection and mass window dependence

The 4q events are selected from the data and Monte Carlo by requiring the neural network output to be larger than -0.3. This cut is varied in steps over the range -0.8 to +0.8 to investigate the stability of the fitted mass and error. Variations of up to 30 MeV/c^2 in the mass value are observed which are small compared with the fit error. Similar studies are made with the semileptonic events varying the probability cut and no significant shifts are found. In addition, the efficiencies and purities quoted in Table 2 do not depend on m_W over the range 79.85-80.85 GeV/c^2. A comparison is also made between the shape of data and corresponding Monte Carlo distributions for all variables used in the preselection of events and in addition, for the 4q channel, in the variables used for choosing the best combination of dijets: the smallest invariant mass difference and the sum of dijet opening angles. No significant discrepancies are observed.

The stability of the result as a function of the mass windows used for both the data and reference Monte Carlo samples in the fits is checked for all decay channels. Observed shifts in m_W are consistent with the differences in the event content of the samples and are not significant compared with the fit errors quoted.

8 Systematic uncertainties

The following sub-sections describe all the systematic errors considered. They are listed in Table 3 for each channel as correlated and uncorrelated errors between the respective decay channels.

8.1 Monte Carlo fragmentation of the $W \to q\bar{q}$ decays

The effect of varying the `JETSET` fragmentation parameters is small and ≤ 10 MeV/c^2 for all the channels studied. However, a more significant effect has been found when `JETSET` is replaced by `HERWIG` [15] to hadronise the partons generated in an independent sample of 400k WW events. The `HERWIG` fragmentation parameters are optimised at the Z using all hadronic events without flavour selection. This new reference sample of `HERWIG` events is then compared with the default `JETSET` sample in the reweighting procedure. Using a large number of Monte Carlo subsamples of the same size as the data, the fitted masses obtained reweighting with each reference sample above are compared and the average shift is quoted as the systematic error. The subsamples are derived from the primary reference of 380k WW events.

8.2 Calorimeter calibrations

The uncertainties in the global calibrations of the ECAL and HCAL energy were assessed to be $\pm 0.9\%$ and $\pm 2\%$ respectively. The energy flow depositions in the data are varied in each direction by these uncertainties. The maximum shifts seen in m_{W} for each calorimeter adjustment are added in quadrature. Common data samples are maintained throughout to suppress statistical fluctuations.

8.3 Jet corrections before the kinematic fit

The discrepancies found in matching reconstructed Monte Carlo jets to data are parametrised as a function of the jet polar angle, θ, to the beam axis (see section 5). To estimate the systematic error, two modified parametrisations are evaluated which accommodate the $\pm 1\sigma$ errors in these discrepancies taking into account the correlations. The largest shift observed in m_{W} for each channel when these modified parametrisations are used to correct the jet energies is taken as the systematic error.

8.4 Initial State Radiation

`KORALW` [6], the main event generator used for the signal events, features QED initial state radiation up to $\mathcal{O}(\alpha^2 L^2)$, i.e. up to second order in the leading-log approximation. The effect of the missing terms on the W mass measurement is estimated by weighting each event in a specially generated `KORALW` sample according to the ratio of first to second order squared matrix elements: $\mathcal{O}(\alpha^1 L^1)/\mathcal{O}(\alpha^2 L^2)$. Treated as data, weighted events selected in each channel are fitted to evaluate the mass and are compared with the corresponding unweighted events to determine the systematic shift.

8.5 Finite reference Monte Carlo statistics

The finite number of Monte Carlo events used as a reference in the reweighting method contributes a systematic uncertainty. The method employed earlier [3] subdivides the Monte Carlo reference sample into smaller samples of equal size each of which is then fitted to the same data. However, the result relies upon an extrapolation to one sample and is less precise than a second method based on a calculation of the statistical uncertainty in m_{W} evaluated from the actual number of Monte Carlo events used. Since the Monte Carlo events are used in bins, this calculation has been performed by combining the uncertainty that is obtained in each bin, taking into account bin-by-bin efficiencies after all analysis steps and the effective number of events allowing for the reweighting procedure. The systematic errors evaluated for each channel by the latter method are given in Table 3.

8.6 Background contamination

For the 4q events, the expected background remaining after all analysis cuts is 15%. The relatively small size of the data sample does not allow a detailed comparison with Monte Carlo and the technique using Z peak data [3] to evaluate the effect of any discrepancies in the background shape and normalisation is re-applied, in this case to the 2-D mass distribution. The systematic uncertainty is smaller than at 172 GeV because the background shape is almost flat.

For the semileptonic events, the error from this source is expected to be small because the total background is only a small fraction of the signal. The error due to the background shape is estimated using data from LEP1, in a similar way as for the hadronic channel. The uncertainty in the background normalisation is estimated by comparing the number of data and expected Monte Carlo events with an electron or muon probability less than 0.1. The resulting error from both sources is very small in all semileptonic channels.

8.7 Colour reconnection in the $\mathrm{q\bar{q}q\bar{q}}$ channel

The colour reconnection effect is studied using Monte Carlo models based on variants of the parton evolution schemes `JETSET` and `HERWIG` both of which have been optimised at the Z. For the `JETSET` study, a single sample of $\mathrm{WW} \rightarrow \mathrm{q\bar{q}q\bar{q}}$ events was generated (for practical reasons using `EXCALIBUR` [14]) and then hadronised in different ways to create: (a) a fully simulated sample with no colour reconnection and (b) three other samples, labelled types I, II and II$'$ [12]. In type I, all events are reconnected according to the degree of string overlap. This is considered unrealistic and a cut, P_{cut}, has been applied to remove 60% of events where the reconnection probability, P_{RECO}, given by:

$$P_{RECO} = 1. - exp^{-0.6*P_{cut}}$$

is less than 30%. These events are replaced in the sample by the corresponding events with no colour reconnection. The fitted mass derived from this mixed sample is greater than that obtained from a completely non-reconnected sample of the same events by $25\pm$ 21 MeV/c^2. For type II events, where the reconnection occurs at the crossing of two vortex lines, the model predicts that 27% of events are reconnected. Applying the same techniques this gives a smaller upward shift, $\triangle m_{\mathrm{W}} = 5\pm$ 15 MeV/c^2. The type II$'$ events are similar, except reconnection is suppressed if there is no reduction of the string length. In this case, $\triangle m_{\mathrm{W}} = 17\pm$ 15 MeV/c^2.

For the `HERWIG` models [13], WW events are generated using `HERWIG` also for the hard process. Three samples are fully simulated with the P_{RECO} parameter, defining the level of reconnection probability, set to 0%, 11% and 60% respectively. The events are not identical at the primary parton level and therefore the masses derived for each case are subject to statistical fluctuations. The shifts obtained relative to the 0% connected sample are -10 and -31 MeV/c^2 respectively with errors of $\pm$25 MeV/c^2 in each case.

In conclusion, none of these models, as applied, predicts any significant effect on m_{W}. The largest uncertainty of 25 MeV/c^2 found in the `JETSET` based models is taken as the quoted systematic error.

The VNI model [17] has not been used to estimate a systematic error because its current implementation does not reproduce particle momentum distributions seen in the data.

8.8 Bose-Einstein effect in the $\mathrm{q\bar{q}q\bar{q}}$ channel

Two separate studies are made. In the first, the weighting method described in [18] is implemented using a `KORALW` Monte Carlo sample. The Bose-Einstein strength and source radius parameters are set to values found in a recent analysis of LEP1 data [19], namely: $\lambda = 0.26 \pm 0.04$ and $\sigma = 4.12 \pm 0.17$ GeV^{-1}. Comparing with the value of m_{W} obtained from the same events unweighted, a downward shift of 43 $\pm$ 25 MeV/c^2 is observed.

The second study is based on KORALW generated events with hadronisation handled by a modified PYTHIA where the Bose-Einstein correlations are described by shifts in final state like-sign boson momenta whilst ensuring that energy-momentum conservation is satisfied [20]. The strength and source radius parameters are obtained from fits to Z data. A comparison is made between mass fits performed where the correlations are restricted to identical bosons within the same W and where in addition correlations between particles from different Ws are also allowed. Again a downward shift in m_{W} of 50$\pm$ 25 MeV/c^2 is observed when Bose-Einstein effects are included between the W decay products.

The larger uncertainty is taken as the quoted error.

8.9 LEP energy

The LEP beam energies are recorded every 15 minutes, and more frequently if significant shifts are observed in the RF frequency of the accelerating cavities. The instantaneous values recorded nearest in time to the selected events are used in the analysis. The relative uncertainty on the LEP energy translates into the same relative uncertainty on the fitted mass, since the beam energy is used directly in the kinematic fits. For the quoted LEP beam energy uncertainty of $\Delta E_b = 25$ MeV [21], a systematic uncertainty of $\Delta m_{\mathrm{W}} = 22$ MeV/c^2 is assigned to all the channels. This is quoted separately from the other experimental systematic errors.

Table 3: Summary of the correlated and uncorrelated systematic errors on m_{W}.

	Δm_{W} (MeV/c^2)			
Source	4q	e	μ	τ
Correlated errors				
MC Fragmentation	35	25	25	30
Calorimeter calibrations	22	21	21	76
Jet corrections	10	5	5	7
Initial State Radiation	10	5	5	5
Uncorrelated errors				
Reference MC Statistics	10	15	13	18
Background contamination	10	6	-	10
Colour reconnection	25	-	-	-
Bose-Einstein effects	50	-	-	-
Total	72	37	36	85

9 The results

9.1 $\mathrm{q\bar{q}q\bar{q}}$ channel

The mass value and statistical error obtained from a single fit to the data using the 2-D method are:

$$\mathrm{WW} \rightarrow \mathrm{q\bar{q}q\bar{q}} \qquad m_{\mathrm{W}} = 80.410 \pm 0.178(\mathrm{stat.}) \pm 0.045(\mathrm{syst.}) \pm 0.056(\mathrm{BE/CR})\ \mathrm{GeV}/c^2.$$

where the theoretical error (BE/CR) comes from the Bose-Einstein and Colour Reconnection systematics in quadrature. The expected statistical error from the RMS spread of the 200 masses obtained from the Monte Carlo subsamples is 0.178±0.009 GeV/c^2 in excellent agreement with the quoted statistical error from the fit to the data. Fig. 1 shows the mass distribution in the window 60 - 86GeV/c^2 for both rescaled masses combined compared with the Monte Carlo reweighted prediction using m_{W} derived from the 2-D analysis.

9.2 e, μ and τ channels

The results quoting the single fit errors are:

$$\begin{array}{lrcl} \mathrm{WW} \to e\nu\mathrm{q\bar{q}} & m_{\mathrm{W}} & = & 80.477 \pm 0.276(\mathrm{stat.}) \pm 0.037(\mathrm{syst.})\ \mathrm{GeV}/c^2, \\ \mathrm{WW} \to \mu\nu\mathrm{q\bar{q}} & m_{\mathrm{W}} & = & 80.307 \pm 0.300(\mathrm{stat.}) \pm 0.036(\mathrm{syst.})\ \mathrm{GeV}/c^2, \\ \mathrm{WW} \to \tau\nu\mathrm{q\bar{q}} & m_{\mathrm{W}} & = & 79.926 \pm 0.525(\mathrm{stat.}) \pm 0.085(\mathrm{syst.})\ \mathrm{GeV}/c^2. \end{array}$$

From 460 randomly chosen subsamples taken in turn from the 380k Monte Carlo WW reference at 80.35 GeV/c^2 the expected errors determined from the means of the distributions of fit errors are ±0.293, ±0.309 and ±0.557 GeV/c^2 for the e, μ and τ channels respectively. Fig. 1 shows the mass distributions for the selected events in each channel and the corresponding Monte Carlo distributions at the reference mass of 80.35 GeV/c^2. The weighted average result for the semileptonic channels is:

$$m_{\mathrm{W}} = 80.337 \pm 0.189(\mathrm{stat.}) \pm 0.040(\mathrm{syst.})$$

.

10 Summary and conclusions

A Monte Carlo reweighting technique is used to measure the mass of the W boson. It is based on the direct comparison of the data mass distributions with those from the Monte Carlo weighted events.

Fully hadronic W decays are selected using a neural network method, while the semileptonic decays are identified individually using three separate selections. The mass variables are determined in a four-constraint fit with rescaling for the 4q channel, and a two-constraint fit for the semileptonic channels. The resulting invariant mass distributions are compared with reweighted Monte Carlo events, and the values of the W mass are extracted in a log-likelihood fit.

Combining all channels the average W mass at 183 GeV is:

$$m_{\mathrm{W}} = 80.374 \pm 0.130(\mathrm{stat.}) \pm 0.041(\mathrm{syst.}) \pm 0.028(\mathrm{BE/CR}) \pm 0.022(\mathrm{LEP})\ \ \mathrm{GeV}/c^2,$$

where the theoretical systematic is due to Bose-Einstein and colour reconnection uncertainties and the last error is due to the LEP energy uncertainty. The masses are combined using weights derived from the statistical and uncorrelated systematic errors added in quadrature.

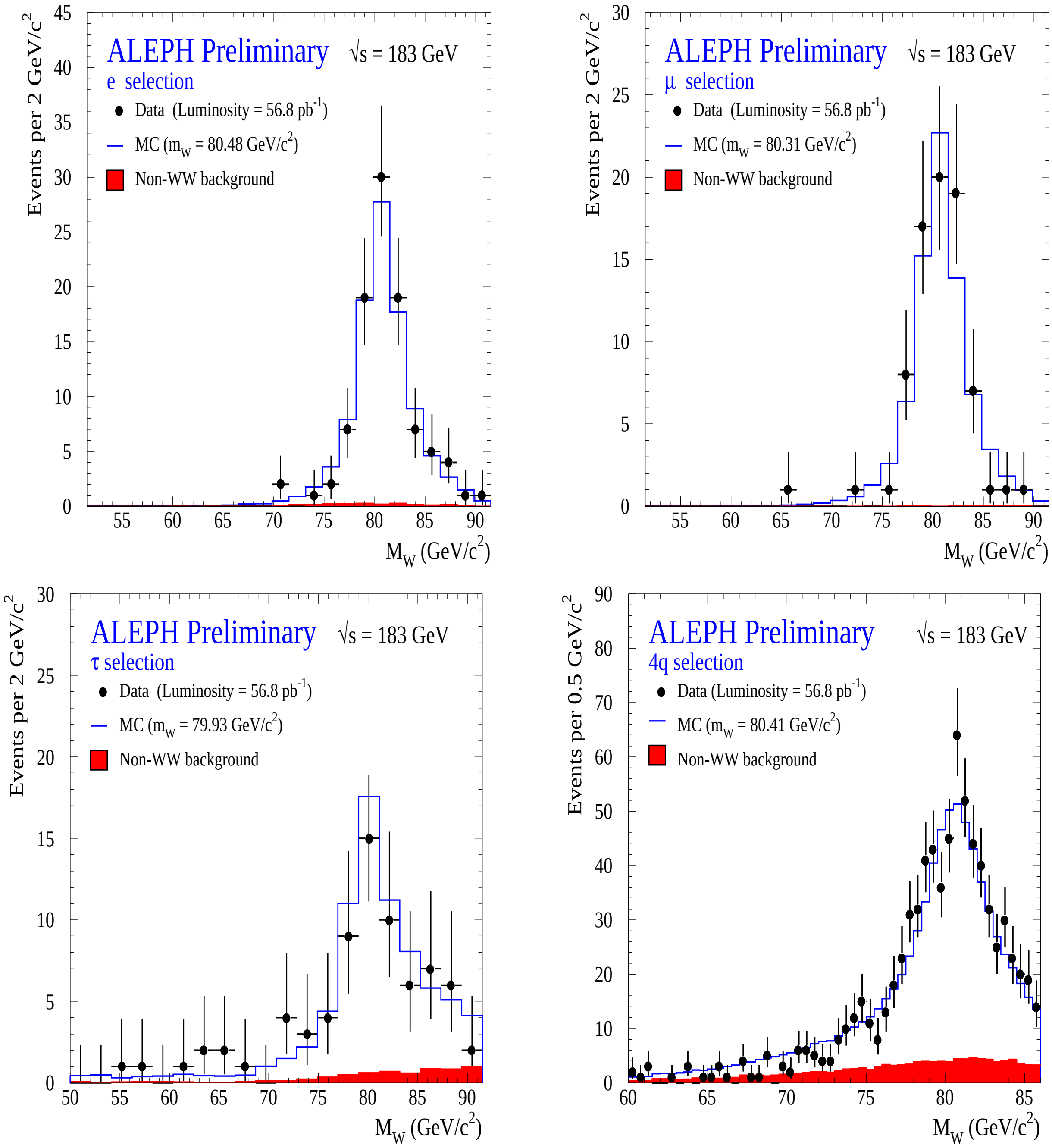

Figure 1: Mass distributions for the e, μ, τ and 4q data (points with error bars), non-WW background (shaded area) and signal+background Monte Carlo with m_{W} values as quoted (solid line histogram).

The masses obtained for the hadronic and semileptonic channels separately can be combined with those determined at 172 GeV by the same final state mass reconstruction method. This gives:

$$M_{\mathrm{W}}^{hadronic} = 80.529 \pm 0.167(\mathrm{stat.}) \pm 0.046(\mathrm{syst.}) \pm 0.049(\mathrm{BE/CR})\ \mathrm{GeV}/c^2.$$
$$M_{\mathrm{W}}^{leptonic} = 80.344 \pm 0.173(\mathrm{stat.}) \pm 0.047(\mathrm{syst.})\ \mathrm{GeV}/c^2.$$

Finally, the masses determined from the direct reconstruction method at 172 and 183 GeV can be combined with the earlier ALEPH results evaluated from the total WW pair cross sections at 161 and 172 GeV. With a $\chi^2/ndf = 0.7/1$, this weighted average of all current measurements of the W mass gives:

$$M_{\rm W} = \quad 80.409 \pm 0.113({\rm stat.}) \pm 0.044({\rm syst.}) \pm 0.022({\rm BE/CR}) \pm 0.023({\rm LEP})\ {\rm GeV}/c^2.$$

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